Waste Management 73 (2018) 232–246

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Evaluation of the environmental sustainability of different waste-to-energy plant configurations

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ARTICLE INFO

Article history:
Received 7 November 2016
Revised 1 June 2017
Accepted 5 July 2017
Available online 17 July 2017

Keywords:
Electric efficiency
Cogeneration
R1
Life cycle assessment
Plant size
Municipal solid waste

ABSTRACT

Residual municipal solid waste (MSW) has an average lower heating value higher than 10 GJ/Mg in the EU, and can be recovered in modern Waste-to-Energy (WtE) plants, producing combined heat and power (CHP) and reaching high levels of energy recovery. CHP is pinpointed as the best technique for energy recovery from waste. However, in some cases, heat recovery is not technically feasible – due to the absence of a thermal user (industrial plant or district heating) in the vicinity of the WtE plant – and power production remains the sole possibility. In these cases, there are some challenges involved in increasing the energy performance as much as possible. High energy recovery efficiency values are very important for the environmental sustainability of WtE plants. The more electricity and heat is produced, the better the saving of natural resources that can be achieved. Within this frame, the aim of this work is to carry out an environmental assessment, through Life Cycle Assessment, of an MSW WtE plant, considering different sizes and operated in different ways, from power production only to full cogeneration. The main assumption is that the electric conversion efficiency increases as the plant size increases, introducing technical improvements thanks to the economies of scale. Impact assessment results were calculated using ReCiPe 2008 methods.

The climate change indicator is positive when the WtE plant is operated in power production only mode, with values decreasing for the increasing size. Values for the climate change are negative when cogeneration is applied, requiring increasing cogeneration ratios for decreasing size. Similarly, the fossil fuel depletion indicator benefits from increase of both the plant size and the cogeneration rate, but it is always negative, meaning that the residual MSW burning with energy recovery always provides a saving of fossil primary energy.

Other indicator values are in general negative and are also beneficially affected by increasing the plant size, but they worsen when increasing the cogeneration rate. The remaining indicators – i.e. human toxicity and terrestrial ecotoxicity – always have positive values, which decrease for increasing plant size and increase as the cogeneration rate increases.

However, the local context should be evaluated carefully with reference to the type of electricity which is substituted and in view of a future massive production of renewable electricity, because conclusions change accordingly.

Finally, it was evaluated that the inclusion of bottom ash recovery – instead of landfilling – can significantly improve the values of several impact assessment indicators.

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Abbreviations: ALO, agricultural land occupation; APCR, air pollution control residues; BA, bottom ash; CC, climate change; CHP, combined heat and power; FA, fly ash; FD, fossil fuel depletion; FE, freshwater eutrophication; FET, freshwater ecotoxicity; FGT, flue gas treatment; HT, human toxicity; IR, ionising radiation; LCA, life cycle assessment; LHV, low heating value; ME, marine eutrophication; MET, marine ecotoxicity; MRD, mineral resource depletion; MSW, municipal solid waste; NLT, natural land transformation; NR, no recovery; OD, ozone depletion; PMF, particulate matter formation; POF, photochemical oxidant formation; R, recovery; SCR, selective catalytic reduction; TA, terrestrial acidification; TET, terrestrial ecotoxicity; ULO, urban land occupation; WD, water depletion; WtE, waste-to-energy.

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http://dx.doi.org/10.1016/j.wasman.2017.07.006
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1. Introduction

The European strategy for waste management attributes primary importance to the prevention of waste production and imposes a priority order in waste management based on: "preparing for re-use; recycling; other recovery, e.g. energy recovery; and disposal" (Directive 2008/98/EC). The recovery of effective goods and material has priority over other forms of recovery and is applied through re-use and recycling. On the other hand, waste disposal to landfills must be considered as the last possibility and limited to pre-treated wastes (not biologically active or not containing easily leachable hazardous substances). Hence, those waste streams for which material recovery is not effectively applicable must follow the path of energy recovery.

According to this framework, energy recovery, mainly through waste thermal treatment, is a fundamental part of the integrated waste management system, especially when related to municipal solid waste (MSW) management, for which material recovery must be accomplished upstream through a separate collection system. Nowadays, combustion processes are the most widespread thermal treatments. Unsorted residual waste (i.e. the waste left downstream of separate collection) may be significantly reduced in mass (about 70–80%) and in volume (about 80–90%) by combustion processes, thus preserving landfill space, and its energy content, which has increased over the past years (MSW Lower Heating Value (LHV) increased from 10.0 to 10.3 GJ/Mg from 2001 to 2010, in the EU, according to Reimann, 2012), can be recovered in modern Waste-to-Energy (WtE) plants.

WtE plants produce energy by recovering the heat contained in the combustion gases, through heat exchangers producing steam. Generally, when only thermal energy is generated, steam may be produced at saturated conditions, while, when electric energy or combined heat and power (CHP) are required, steam is superheated. Superheated steam may be supplied to a steam turbine for the production of power only, using a condensing turbine, or for CHP, using a back pressure or intermediate steam extraction turbine. The CHP production allows high levels of energy recovery to be achieved and it is pinpointed as one of the best techniques for energy recovery from waste (European Commission, 2006). It is also the technical solution that allows high values according to the R1 criteria – directly linked to the energy efficiency – to be reached (Directive 2008/98/EC). The introduction of the R1 criteria has proved to be an incentive for WtE plants in Europe to improve their energy efficiency, as reported by CEWEP (Reimann, 2009, 2012). However, in some cases, heat recovery is not technically feasible – due to the absence of a heat user (industrial plant or district heating) in the vicinity of the WtE plant – and thus power production remains as the only option. In these cases, there are some challenges involved in increasing the energy performance as much as possible: high values are obtainable only for large WtE plants (Pavlas et al., 2011; Consonni and Viganò, 2012).

High energy recovery efficiency values are very important also for the environmental sustainability of WtE plants. The more electricity and heat is produced, the better the saving of natural resources may be achieved. Pavlas et al. (2011) evaluated the benefits of energy recovery in WtE by CHP applying a method based on primary energy saving (PES). Damgaard et al. (2010) showed that CHP is able to provide a greater saving, in life cycle assessment (LCA) evaluations, than recovering only electricity. Grosso et al. (2010) calculated the R1 formula (see Section 2.1) and the exergy efficiency for waste-to-energy plants operating in Europe, revealing some significant differences in their performance, mainly related to the average size and to the availability of a heat market (district heating). Lombardi et al. (2015) highlighted that "in the case of only electricity production, the achievable efficiency values are strongly dependent on the plant size: for large plant size, where advanced technical solutions can be applied and sustained from an economic point of view, net electric efficiency may reach values up to 30–31%". Of course, it may happen that a large plant uses poor technical solutions, or vice versa a small plant uses improved technical solutions. However the general trend shows that the advanced technical solutions are applied in large scale plants, leading to higher electric efficiencies (Consonni et al., 2017).

Within this frame, the aim of this work is to carry out an environmental assessment, through LCA, of different configurations of MSW WtE plants, i.e. power production only vs. increasing degrees of cogeneration. Additionally, sizes ranging from small to large plants were considered, gradually including the technical improvements that may increase the overall plant performance.

2. Materials and methods

The methodology applied for evaluating the environmental burdens of the WtE process is LCA (ISO, 2006a, 2006b), so the following paragraphs report the different steps included in the methodology: goal and scope definition, inventory analysis, impact assessment.

2.1. Goal and scope definition

Definition of the goal is the first phase of the LCA, in which the purpose of the study is described. It identifies and defines the object of the assessment.

The aim of this study is to evaluate the environmental burdens – throughout the entire life cycle – of the residual MSW thermal treatment by combustion with energy recovery (i.e. WtE), comparing different possibilities for energy production, from power production only to full cogeneration, comparing different plant sizes.

The analysis was carried out in reference to the assumed material composition for the residual MSW reported in Table 1, along with the resulting chemical composition (Consonni and Viganò, 2012), which supplies an LHV of about 10,544 GJ/Mg (calculated on the chemical composition basis).

The WtE plant size was assumed to range from 12.5 to 300 MW in terms of thermal power input, hence from small to large size, according to Consonni and Viganò (2012). Along with increase of the plant size, gradual technical improvements to the plant were introduced, which enhance the overall plant energy performance (Consonni and Viganò, 2012). The main design parameters for each considered size are reported in Table 2. Assumed parameters are coherent with design parameters commonly found in EU plants (Lombardi et al., 2015; Consonni et al., 2017).

For each plant size, the performance was first calculated in the case of power production only. The produced electric energy is assumed to substitute the electric energy produced by the Italian

Table 1
Material and chemical composition assumed for the residual MSW.

Material composition [% in mass]		Chemical composition [% in mass]	
Paper and cardboard	12.00	C	27.59
Organic matter	33.00	H	4.23
Garden waste	9.00	O	17.39
Plastics	15.00	S	0.04
Metals	6.00	N	0.67
Wood	6.50	Cl	0.26
Glass	9.50	F	0.004
Textiles	9.00	Ashes	16.46
		Moisture	33.37

Table 2
Assumed design parameters for plants of different sizes.

Thermal power input – plant size [MW]	12.5	25	50	100	200	300
MSW throughput [Mg/y]	33,800	67,600	135,199	270,398	540,797	811,195
Steam maximum pressure [bar]	30	35	40	45	65	70
Steam maximum temperature [°C]	350	380	400	420	440	450
O_2 in the flue gas at the boiler exit [% vol.]	7.5	7.0	6.5	6.0	6.0	6.0
Flue gas temperature at the stack [°C]	180	180	135	135	135	135
Turbine isentropic efficiency	0.7	0.73	0.78	0.8	0.845	0.865

electric energy mix. Then steam extraction at 3 bar was introduced and the performance was calculated assuming an increasing ratio (from 0 to 1) of extracted steam with respect to the overall steam flow rate. The extracted steam mass flow releases its enthalpy content to district heating water, until complete condensation. The heat exchanger efficiency was assumed 0.9. Available thermal power is assumed to be delivered to district heating for 166 days per year and 12 h per day, according to the Italian limitations imposed for the regions of central Italy (Law n. 10/91 and DPR n. 412/93 and modifications). The benefits of cogenerating heat are accounted for as avoided effects for substituting the conventional thermal energy produced by a natural gas boiler, in residential heating applications.

The primary function of the analyzed systems is the treatment of residual MSW, for this reason the functional unit assumed for the comparison is 1 Mg of residual MSW. While to account for co-products (mainly electricity and heat) the system expansion approach was applied (Finnveden et al., 2009; European Commission, 2010), by including the avoided effects caused by substitution of products from conventional processes.

Within the analyzed system boundary, the following processes were included: transportation of MSW to the Waste-to-Energy plant, combustion and energy recovery processes, manufacturing processes of chemicals required for flue gas treatment (FGT), transportation and final disposal of bottom ash (BA), transportation and disposal/treatment of fly ash (FA) and air pollution control residues (APCR).

Processes regarding entering flows such as chemicals, or exiting flows such as electricity or heat, and transportation of MSW or residues, were described in the inventory using appropriate records retrieved from the ecoinvent database (Wernet et al., 2016), as detailed in the following paragraphs.

Landfilling was considered as the basic option for BA disposal, while in an improved case, aluminum, steel and inert recovery are considered.

In the life cycle assessment approach, a system even wider than the assumed one could be considered, including the avoided alternative of landfilling the residual MSW. However, it is well-know that landfilling is the less desirable option for waste management (Directive 2008/98/EC) and alternative waste management strategies need to be implemented to reduce the waste management sector environmental impacts (Bogner et al., 2008). It is not within the scope of this work to show the benefits that can be obtained by diverting MSW from landfill to WtE, which is a consolidated result (see among the numerous papers Fernandez-Nava et al. (2014) and Belboom et al. (2013)). For this reason, the system boundary was not expanded to include the avoided landfilling.

Impact assessment results were calculated using midpoint indicators defined by the ReCiPe 2008 method, according to the hierarchist perspective (Goedkoop et al., 2009). Results are reported with respect to the selected functional unit equal to 1 Mg of residual MSW, thus allowing the comparison of different plant sizes.

Additionally, the values of R1, according to Directive 2008/98/EC (Eq. (1)), were calculated and plotted against the plant size, together with some impact assessment indicators:

$$R1 = (Ep - (Ef + Ei))/(0.97(Ew + Ef)) \quad (1)$$

where Ep is the weighted sum of gross electric and thermal energy generated by the plant (GJ/year), with electric energy weighted by a factor of 2.6 and thermal energy weighted by a factor of 1.1; Ef is energy in the fuels[1] contributing to the production of steam (GJ/year); Ew is energy in the waste (GJ/year); Ei is energy imported other than Ew and Ef (GJ/year); 0.97 is a coefficient accounting for energy losses associated with bottom ash and radiation. According to Directive 2008/98/EC, to be considered a recovery plant, a WtE plant must reach R1 higher than 0.65 (or, for plants permitted before January 1st 2009, R1 higher than 0.60). Possible adjustments of the R1 criteria, according to the country specific climate condition, are left open to Member State.

2.2. Inventory analysis

In this LCA phase, all the inputs and outputs occurring in the life cycle of the system previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary, either into or out of the system itself.

Inventory data are gained by modeling the processes and by using literature data. Details are given in the following paragraphs for each process included within the system boundary.

2.2.1. Waste-to-energy

The WtE process was simulated by a home developed thermodynamic model (using Engineering Equation Solver, F-Chart Software). The model requires as input the specific waste chemical composition and mass flow rate. Complete combustion of the entering waste is assumed with the exception of part of the fixed carbon, equivalent to 3% in mass of the BA. The energy balance in the combustion chamber is performed assuming an integrated boiler grid furnace, the volumetric content of oxygen assigned for each plant size (Table 2), combustion temperature equal to 1000 °C, and heat losses. The combustion gas mass flow rate is calculated and used, in turn, to calculate the steam mass flow rate produced in the boiler, assuming the assigned levels of pressure and temperature for the superheated steam for the different plant sizes (Table 2). The steam expansion is calculated considering different isentropic efficiencies of the turbine: the entire steam mass flow rate expands to the condenser pressure equal to 0.09 bar in the case of electricity production only. On the contrary, in the cogeneration case, a fraction (from 0.1 to 1) of the steam is extracted at 3 bar, while the remaining part expands down to the condenser pressure equal to 0.09 bar. Of course, for an increasing steam extraction fraction, the electric power output decreases, while the thermal power production increases.

The in-plant consumptions represent a quite important part of the gross power and are mainly due to waste handling, general

[1] Fuels are intended as "combustible non waste substances" (e.g. diesel, natural gas) compliant with the Fuel Quality Directive 2009/30/EC, used for start-up and shutdown of the incineration process, including fuels to maintain required temperatures > 850 °C by using auxiliary burners.

auxiliaries, bottom and fly ash handling and FGT. The FGT contribution is the main one and may range from 10 to 80 kWh per Mg of waste, depending on the type of applied technology: the value of 75 kWh per Mg of waste was assumed in this study (Damgaard et al., 2010). The considered FGT was based on double filtration with dry flue gas cleaning using sodium bicarbonate ($NaHCO_3$) and activated carbon injection, followed by selective catalytic reduction (SCR). The total in-plant specific consumption – i.e. the part of the produced electricity consumed within the plant itself – was assumed equal to 105 kWh per Mg of waste (Reimann, 2012).

The model provides as output: net electric power, thermal power, BA, APCR, stack emissions of hydrogen chloride (HCl), hydrogen fluoride (HF), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), Total Organic Carbon (TOC), the sum of cadmium (Cd) and thallium (Tl), mercury (Hg), the sum of other heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-para-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) and ammonia (NH_3). Stack emissions were evaluated assuming the concentrations reported in Table 3, which are typical values found in European WtE plants (Vehlow, 2015; European Commission, 2006), definitely lower than the Directive 2000/76/EC limits, reported also in Table 3 for comparison. The calculated specific flue gas flow rate decreased slightly with the plant size, as a consequence of the reduced volumetric content of residual oxygen assumed in the different cases (6648–6515 dry Nm^3 at 11% O_2 per Mg of MSW).

Consumption of $NaHCO_3$, to reduce the concentrations of HCl, HF and SO_2 at the stack, was calculated assuming a value 1.25 times higher than the stoichiometric one, calculated on the basis of the pollutant contents and the target values at the stack. NH_3 consumption in the SCR was calculated considering a value 1.1 times higher than the stoichiometric one. Activated carbon consumption is calculated as 5% in mass with respect to the $NaHCO_3$ mass flow rate, resulting in specific consumption values within the common range (European Commission, 2006). The specific consumption of chemicals and the specific production of residues are the same for the different cases analyzed, the input MSW chemical composition being constant, and are reported in Table 3.

Carbon dioxide (CO_2) emissions were calculated from the MSW chemical composition (Table 1), considering only those originating from non-renewable materials. Carbon contained in materials as paper and cardboard, organic matter, garden waste, wood is of renewable origin. Textiles might be of both of renewable and non-renewable origin, thus it was assumed that half of textile materials are renewable. According to these assumptions the renewable carbon is 0.158 kg per kg of MSW, corresponding to about 57% of the total carbon. Consequently, the non-renewable carbon, contained in plastics and half textiles, results 0.118 kg per kg of MSW, about 43% of the total carbon, producing 431 kg of non-renewable CO_2 per Mg of MSW.

2.2.2. Waste transportation

As the plant size increases, an increased average transportation distance was assumed for the feeding MSW, as reported in Table 4. However the authors are aware that the real situations might be more complex. Small plants might receive waste from large, sparsely populated regions, while large plants might often receive waste from densely populated cities with short distances. To take into account this possibility, a sensitivity analysis with respect to the transportation distance was carried out, assuming for all the considered cases an average transportation distance of 100 km, which means to increase the preliminarily assumed distance for small size plants and decrease it for large size plants.

BA and FA transportation distances of 100 and 650 km, respectively, were assumed.

In both cases, the transportation inventory was retrieved from the ecoinvent database (Wernet et al., 2016) using the appropriate record referring to 7.5–16 Mg lorry.

2.2.3. Residues treatment and disposal

The reference scenario assumed disposal of BA in a landfill for inert waste, retrieving the inventory from the appropriate ecoinvent record (Wernet et al., 2016).

Table 3
Pollutant emission concentrations at the WtE stack, reactants consumption and residues production.

		Directive 2000/76/EC*		Assumed concentrations at the stack*
Particulate matter	mg/Nm^3	10	30	2
HCl	mg/Nm^3	10	60	2.5
HF	mg/Nm^3	1	4	0.05
SO_2	mg/Nm^3	50	200	7.5
NO_2	mg/Nm^3	200	400	60
CO	mg/Nm^3	50	100	25
TOC	mg/Nm^3	10	20	5
Cd and Tl	mg/Nm^3	0.05		0.025
Hg	mg/Nm^3	0.05		0.025
Sb, As, Cr, Co, Cu, Mn, Ni, V, Sn	mg/Nm^3	0.5		0.25
PAHs	mg/Nm^3	0.01		0.005
PCDDs/PCDFs	ng/Nm^3	0.1		0.05
NH_3	mg/Nm^3	–		5

* Limits and assumed concentrations are referred to dry flue gas and oxygen volumetric content equal to 11%

Specific reactants consumption			Specific solid residues production		
$NaHCO_3$	kg/Mg_{MSW}	10.5	APCR	kg/Mg_{MSW}	41.6
Activated carbon	kg/Mg_{MSW}	0.53	BA	kg/Mg_{MSW}	135.7
NH_3	kg/Mg_{MSW}	0.50			

Table 4
Average transportation distances assumed for the entering MSW.

Plant size [MW]	12.5	25	50	100	200	300
Assumed distance [km]	25	50	100	100	200	200

As an alternative to landfilling, BA was assumed to be treated with the aim of recovering metals and inert materials, requiring about 4 kWh per Mg of BA and recovering 13.3 kg of aluminum scrap, 78.1 kg of steel scrap and 751 kg of inert waste from 1 Mg of BA, while the remaining 87.6 kg are landfilled (CiAl, 2010). The data used for aluminum and steel scrap recovered are not far from those used by Arena et al. (2015), while data assumed for inert recovery are more optimistic (Arena et al. report that per 1 Mg of BA, 454 kg of inert waste can be recovered, while 423 kg of inert waste are landfilled). From 1 kg of aluminum scraps, 0.78 kg of secondary aluminum can be produced (CiAl, 2010) (impacts for secondary aluminum production were accounted for considering the appropriate ecoinvent record), avoiding the same amount of primary aluminum (avoided impacts accounted for considering the appropriate ecoinvent record) (Wernet et al., 2016).

Similarly, from 1 kg of steel scrap 0.90 kg of secondary steel can be produced (CiAl, 2010) (impacts for secondary steel production were accounted for considering the appropriate ecoinvent record), avoiding the same amount of primary steel (avoided impacts were accounted for considering the appropriate ecoinvent record) (Wernet et al., 2016).

It is assumed that each kg of recovered inert waste is used in concrete preparation, substituting respectively 0.4 kg of gravel and 0.6 kg of sand (CiAl, 2010).

The results related to the BA recovery are presented in Section 3.5.

In the FGT, a double filtration stage was assumed; thus, FA is removed mainly in the first filtration stage, before acid gas treatment and activated carbon injection take place. Thus the products from the acid gas removal reactions, the excess of reactants and exhausted activated carbon are collected in the second filtration stage. It was assumed that FA undergoes the inertization process, requiring 0.225 L of water per kg of fly ash (inventory from ecoinvent record; Wernet et al., 2016) and 0.07 kg of hydrated lime (inventory from ecoinvent; Wernet et al., 2016 record) (Rigamonti et al., 2012). After inertization, the fly ash is sent to disposal for backfilling of mines, using the appropriate ecoinvent record (Wernet et al., 2016). The APCR collected in the second filtration stage, mainly constituted by residual sodium salts, can be sent for recovery in the Solval® process. The process is made for the production of a brine (to be reused by Solvay for sodium carbonate production) and of some hazardous solid residues that are landfilled. The average distance between the WtE plant and the recovery platform was assumed equal to 110 km and the transport was inventoried using the appropriate ecoinvent record referring to 7.5–16 Mg lorry (Wernet et al., 2016). The treatment of 1 Mg of residual sodium salts allows the recovery of 743 kg of sodium chloride (NaCl; record from ecoinvent; Wernet et al., 2016) and it requires 30 kWh of electricity (Turconi et al., 2011) recovered (i.e., avoided). The scrap from the recovery treatment (i.e. 146 kg per Mg of residual sodium salts) is disposed in a landfill assumed to be located at 300 km (ecoinvent records; Wernet et al., 2016).

2.2.4. Utilities and chemicals

Inventory data for chemicals, diesel, conventional heat and electricity production were retrieved from the ecoinvent database (Wernet et al., 2016). In particular, with reference to the electricity production, the record referring to the Italian electric mix was selected as the base case in the reference scenario. In ecoinvent version 3.0 (Wernet et al., 2016) the annual production volume of all electricity production datasets are taken from IEA/OECD statistics and are valid for 2008. The share of electricity for the Italian electric mix in 2008, according to the IEA/OECD statistics (IEA, 2008), is the following: coal 15.2%; oil 9.9%; gas 54.1%; biofuels 1.4%; waste 1.0%; hydro 14.8%; geothermal 1.7%; solar PV 0.1%; wind 1.5%; other sources 0.3%. Then, in the sensitivity analysis, the Italian electric mix was substituted with the electricity records that referred respectively to Spain, Poland and Norway. The share of electricity for the Spanish electric mix in 2008 is the following: coal 15.9%; oil 5.7%; gas 38.5%; biofuels 0.8%; waste 0.5%; nuclear 18.8%; hydro 8.3%; solar PV 0.8%; solar thermal 0.01%; wind 10.5%; other sources 0.1% (IEA, 2008). While the share of electricity for the Polish electric mix 2008 is the following: coal 90.5%; oil 1.8%; gas 3.0%; biofuels 2.3%; hydro 1.8%; wind 0.5%; other sources 0.04% (IEA, 2008). Finally, the share of electricity for the Norwegian electric mix 2008 is the following: coal 0.09%; oil 0.02%; gas 0.31%; biofuels 0.24%; waste 0.09%; hydro 98.5%; wind 0.64%; other sources 0.12% (IEA, 2008).

For the $NaHCO_3$ modeling production, the approach suggested by Biganzoli et al. (2015) was adopted, considering the two sequential production steps: (1) soda production (Na_2CO_3) through the Solvay process (step 1) retrieved from ecoinvent (Wernet et al., 2016); (2) soda reaction of with water and CO_2 to produce $NaHCO_3$ with a high level of purity (step 2). For step 2 the following inputs per 1 Mg of $NaHCO_3$ were considered: 126 Lof water, 309 kg of CO_2 (from ecoinvent; Wernet et al., 2016) and 336 MJ of electricity (Biganzoli et al., 2015).

CO_2 is produced during the activation of sodium bicarbonate when it is injected into the flue gas of the WtE plants: stoichiometric calculation results in 262 g of CO_2 emitted per 1 kg of $NaHCO_3$, which were included in the analysis.

3. Results and discussion

Environmental results are presented according to the Life Cycle Impact Assessment. This LCA phase examines the mass and energy inventory input and output data for a product system and translates the inventory data into environmental impacts so as to better identify their possible environmental relevance and significance. This translation uses, where possible, numerical indicators for specific subjects or categories that reflect in some manner the system's environmental loading or resources depletion for that category. These indicators then constitute an environmental loading and resources depletion profile for a system. This profile, with possible further analysis and weighting, is intended to provide an additional useful perspective on the possible environmental significance in one or more general areas of resources, natural environment and human health.

Impact assessment results were calculated using midpoint indicators defined by the ReCiPe 2008 method, according to the hierarchist perspective (Goedkoop et al., 2009). The ReCiPe 2008 method impact assessment indicators are: climate change (CC); ozone depletion (OD); terrestrial acidification (TA); freshwater eutrophication (FE); marine eutrophication (ME); human toxicity (HT); photochemical oxidant formation (POF); particulate matter formation (PMF); terrestrial ecotoxicity (TET); freshwater ecotoxicity (FET); marine ecotoxicity (MET); ionising radiation (IR); agricultural land occupation (ALO); urban land occupation (ULO); natural land transformation (NLT); water depletion (WD); mineral resource depletion (MRD); fossil fuel depletion (FD).

3.1. Energy analysis results

Fig. 1 shows the results in terms of the net electric efficiency, R1 value and specific electric energy production for the power production only mode at increasing plant size. The net electric efficiency of the plants rises from 0.18 to 0.27 for increasing size, thanks to the improvement in the design parameters previously reported in Table 2. However, the R1 criterion is not accomplished if the plant size is less than 50 MW. Thus, in order to comply with the R1 criteria, for small plants it is necessary to operate in cogeneration mode

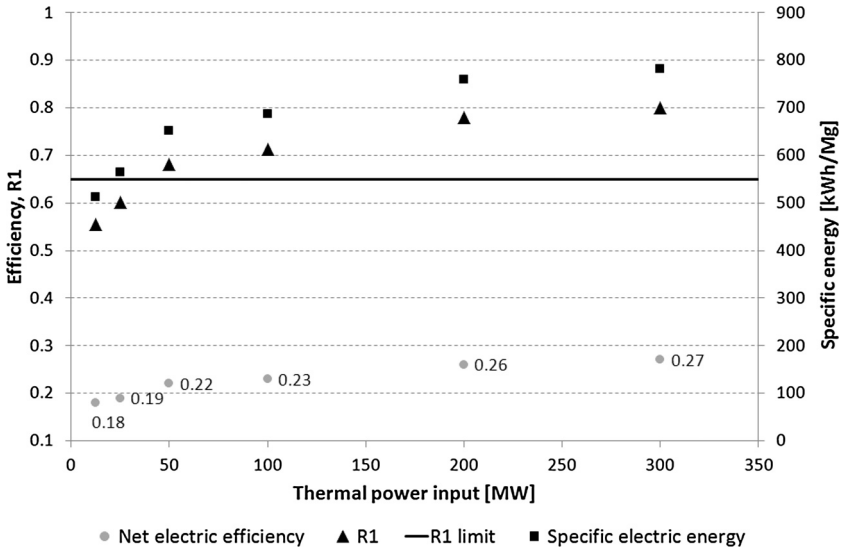

Fig. 1. Net electric efficiency, net specific energy and R1 vs. the plant size, for the case of power production only.

(Grosso et al., 2010) or in heat only mode, as common in the Scandinavian countries (Lausselet et al., 2016).

Fig. 2 shows how cogeneration – for an increasing fraction of steam extracted at 3 bar – allows the R1 values to be improved. However, for small plants (12.5 MW) the minimum value of 0.65 is not reached even in full cogeneration mode, while for plant size 25 MW at least 50% of the steam at 3 bar must be extracted and used for thermal power production, in order to comply with the R1 criteria. Renouncing to the production of part of the electricity when operating in cogeneration mode, might influence the economic issues of the plant. The economic issues are not within the scope of this work, however it is suggested that a full economic analysis for the cases presented in this work would be useful in the future.

3.2. Impact assessment

For completeness, the final values of each indicator included in the ReCiPe2008 impact assessment method are reported in the tables in the Appendix A, for each plant size and each cogeneration ratio. For reasons of conciseness, in the following, the results are commented upon grouping together indicators showing the same behavior and reporting the graphs for some of them in order to better illustrate the discussion.

Fig. 3 shows the values of the climate change for the increasing cogeneration rate. Negative values of the indicator can be reached only by cogeneration of heat and power. Plants in the range 200–300 MW need to operate in cogeneration mode – at least 10–20% of steam should be extracted – to obtain CO_2 savings. Medium plants (50–100 MW) and small plants (12.5–25 MW) require at least 30–40% and 60–70% steam extraction, respectively, to obtain CO_2 savings. The increasing cogeneration rate is, however, beneficial with respect to the climate change indicator for all the plant sizes. Fig. 4 shows how the increasing cogeneration rate allows for increasing contributions to avoiding conventional thermal energy impacts. If the plant size is increased from 12.5 to 300 MW, the climate change indicator drops from 148 to 6.7 kg of CO_2 eq. per Mg of MSW, with a reduction of 95%, while if for

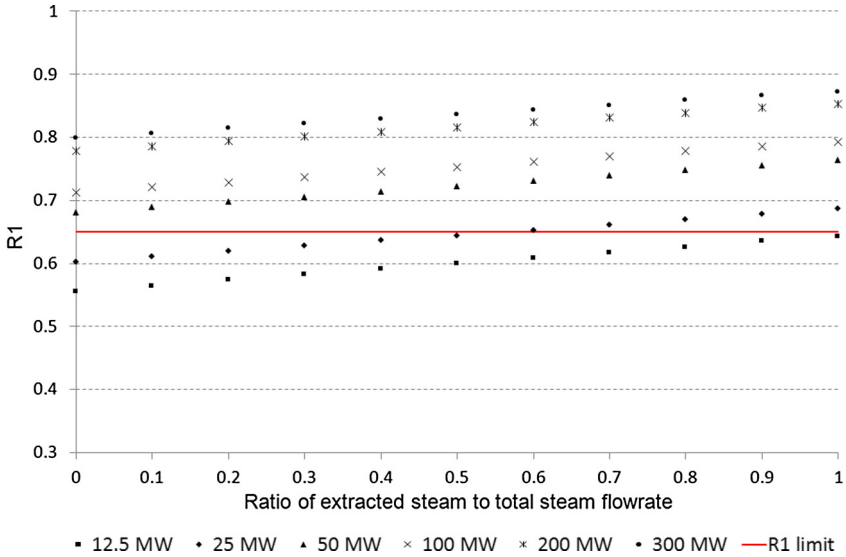

Fig. 2. R1, for different plant sizes, vs. the fraction of steam extracted at 3 bar.

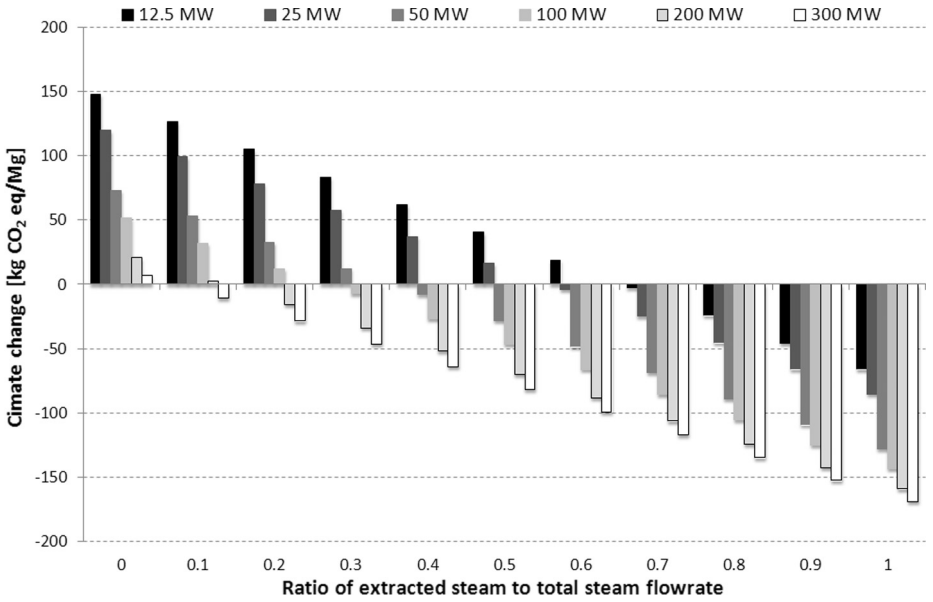

Fig. 3. Climate change indicator, for different plant sizes, vs. the fraction of steam extracted at 3 bar. Base case: BA landfilling.

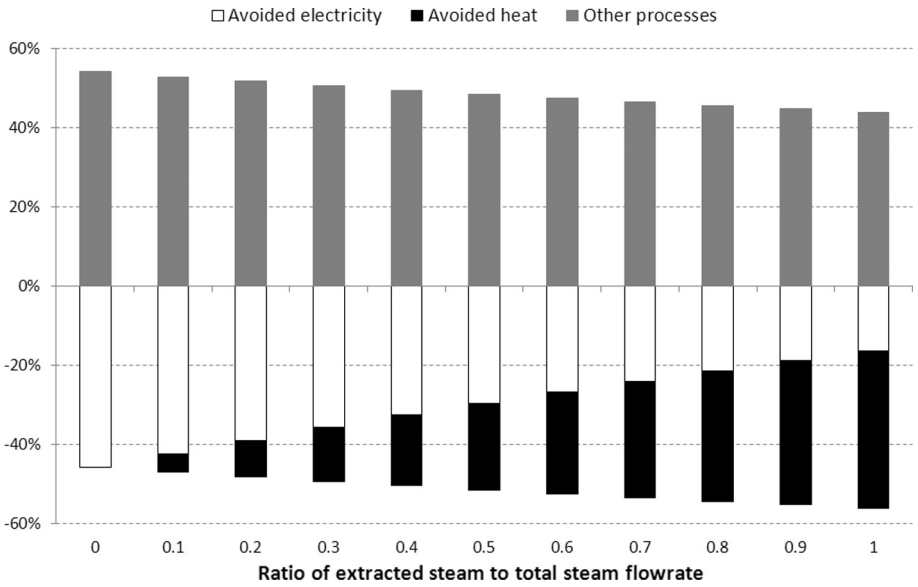

Fig. 4. Contributions to climate change indicator from processes included in the analyzed system vs. the fraction of steam extracted at 3 bar. Results are reported in the case of 50 MW plant size.

the 12.5 MW plant the cogeneration rate is increased to 1, the climate change indicator becomes −66, an improvement of 145%. Similar evaluations can be done for the other plant sizes. Thus it is evident that cogeneration has a stronger effect on improving this environmental indicator.

Additionally, the authors would draw the reader's attention to the comparison between the trends of R1 and climate change vs. the cogeneration rate. It appears that compliance with the R1 criterion does not necessarily imply savings in the climate change indicator. R1 is higher than 0.65 for the plants with size equal or higher than 50 MW, with or without cogeneration (Fig. 2). So for this type of plants cogeneration is not necessary to comply with R1 criterion. Thus, it is observed that R1 criterion does not favour or push cogeneration at least for medium-large size plants, while it requires the cogeneration for small size plants (25 MW). On the contrary, climate change is positive for all the sizes when cogeneration is not applied and it is strongly decreased, to negative values, when cogeneration is applied (Fig. 3). Potentially, a different criterion based on a negative climate change indicator, which would favour cogeneration, would provide higher environmental benefits concerning both global warming and fossil resource saving.

Similarly to climate change, the fossil fuel depletion indicator (Fig. 5) benefits from increase of both the plant size and cogeneration rate, but, unlike the climate change results, it is always negative, meaning that the residual MSW burning with energy recovery always provides fossil primary energy saving. Also in this case, if we increase the plant size from 12.5 to 300 MW the fossil fuel indicator has a lower improvement (48–18%), with respect to increasing the cogeneration rate to 1 (90–52%). Thus it is evident that cogeneration has a stronger effect on improving also this environmental indicator.

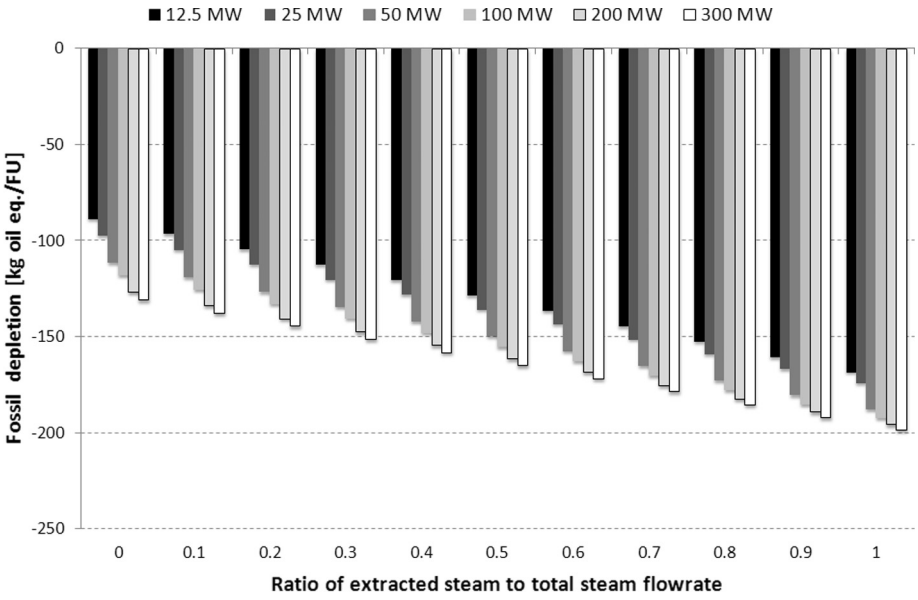

Fig. 5. Fossil fuel depletion indicator, for different plant sizes, vs. the fraction of steam extracted at 3 bar.

The following other indicators present negative values for all the plant sizes and cogeneration rates: ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, particulate matter formation, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, mineral depletion, water depletion, agricultural land occupation, urban land occupation and natural land transformation. Photochemical oxidant formation has almost always negative values, with the exception of the cases of small plants and high cogeneration rates. However, their behavior is different from the previously highlighted ones. These indicators take advantage of the increase of plant size, with higher negative values, while the benefits are reduced as the cogeneration rate increases. As an example of this type of trend, Fig. 6 shows the terrestrial acidification indicator and Fig. 7 shows the percent contributions to the total terrestrial acidification indicator value from electricity recovery (avoided electricity), heat recovery (avoided heat) and other considered processes (which supply positive contributions), in the case of the 50 MW plant size. From this figure, it is clear that the main beneficial effects for this indicator (and for the other indicators listed above) come from the electricity production, while the contribution derived from heat recovery is much less. Thus, for an increasing cogeneration rate – i.e. increasing heat production and decreasing electricity production – the indicator values become worse.

On the contrary, the other remaining indicators present positive values. It means that the avoided effects (i.e. mainly avoided conventional electricity and avoided conventional heat) are not enough to compensate the impacts from WtE related processes, mainly because the impact produced by the conventional processes (i.e. electricity and heat) for these categories are lower than those generated by the WtE case. In particular, human toxicity and terrestrial ecotoxicity always have positive indicator values, which

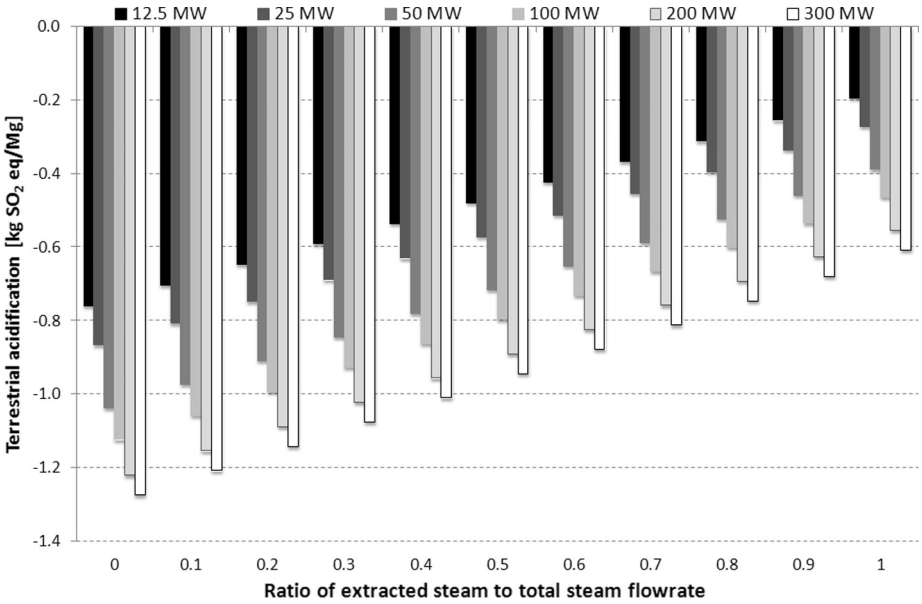

Fig. 6. Terrestrial acidification indicator, for different plant sizes, vs. the fraction of steam extracted at 3 bar.

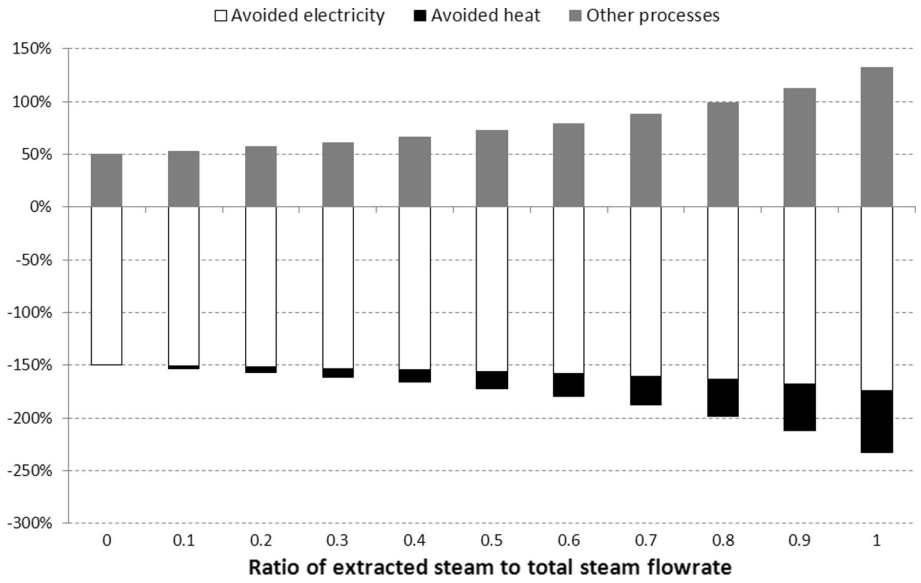

Fig. 7. Contributions to terrestrial acidification indicator from processes included in the analyzed system vs. the fraction of steam extracted at 3 bar. Results are reported in the case of 50 MW plant size.

decrease for increasing plant size and increase as the cogeneration rate increases, as shown by Fig. 8 for human toxicity as an example. The slight improvement observed for the increasing plant size is linked to the possibility of operating the combustion with lower air excess and thus with the emission of a lower volume of flue gases per unit of mass of residual MSW. As a matter of fact, the main contribution to the human toxicity indicator derives from the stack emissions (Fig. 9). The avoided effects are supplied mainly by electricity recovery, while heat recovery has rather less influence. The decrease of electricity production along with the cogeneration rate worsens the avoided effects, increasing the final value of the indicator.

In conclusion, it resulted that not all the indicators can be improved simultaneously by the same strategy (i.e. increasing/reducing the size; only power production/cogeneration; increasing/decreasing the cogeneration rate). Priorities among the environmental indicators must be set, taking into considerations local environmental conditions and including factors, which are out of the scope of this work, as economic and social ones.

3.3. Sensitivity of the impact assessment results to change of the electric energy mix

A large number of indicators are mainly affected by the avoided effects due to electricity recovery. As previously stated, the recovered electric energy is assumed to substitute an equivalent amount of electricity produced by the Italian electric mix, as described by the ecoinvent record used. Thus the presented results are valid strictly for WtE plants located in Italy. Since it is quite well known that several impact assessment indicators are strongly affected by the local electricity mix results (Evangelisti et al., 2014; Burnley et al., 2015; Arena et al., 2015), the impacts were recalculated substituting the Italian electricity mix with, respectively, the Polish, Spanish and Norwegian ones (using the records available in ecoinvent), as concerns the avoided effects due to electricity recovery in the WtE plants. In Poland almost all the electricity is produced from coal, resulting in a very high specific CO_2 emission (0.303 kg CO_2 eq./MJ), while in Spain basically the use of nuclear energy reduces the electric energy specific CO_2 emission (0.176 kg CO_2 eq./MJ), with respect to the Italian one (0.189 kg CO_2 eq./MJ). The Norwegian case was selected in order to consider a very high renewable share, which in the specific case is given by hydroelectric energy. For the Norwegian case the electric energy specific CO_2 emission is very low (0.006 kg CO_2 eq./MJ).

Fig. 10 shows the results for all the ReCiPe2008 impact assessment indicators in the case of 50 MW WtE plants operated in power production only mode. Very different conclusions can be drawn with respect to the base case; for example, WtE plants located in Poland act as a carbon sink even without applying cogeneration. On the contrary, the positive climate change calculated for Spain is much higher than the value calculated for Italy. The worst case, finally, is the Norwegian one: obviously displacing hydroelectric electricity with the electricity produced by the WtE strongly deteriorates the indicator values. Thus, it is recommended that specific analyses are performed for specific countries, also considering that the energy mix of a country is continually evolving towards a greater use of renewables.

3.4. Sensitivity of the impact assessment results to change of the MSW transportation distance

Concerning MWS transportation distance, the base assumption was related to an increasing distance as the plant size increases, as reported in Table 4. The contribution from the transportation phase to the total positive values[2] of the climate change indicator is reported in Table 5, for the different plant sizes, in the case of only power production. The contributions ranges from 0.7 to 5.5% as the distance increases. However, if also the absolute values of the avoided effects are included in the calculation[3], the transport contribution decreases to 0.4–2.8%.

If the assumed transportation distance is changed to the same value of 100 km for all the plants the contribution to the positive values of climate change is equal to 2.8% for all the cases, while it ranges from 1.4 to 1.7%, if also the absolute values of the avoided

[2] Contribution of transportation phase to the total positive effects = $\frac{CC_{transport}}{\sum_{i=1}^{n} CC_{i,pos}}$, where $CC_{transport}$ is the climate change indicator value per functional unit due to the transport; $CC_{i,pos}$ is the climate change indicator value per functional unit of other processes providing positive impact.

[3] Contribution of transportation phase to the total algebraic sum of positive and negative effects = $\frac{CC_{transport}}{\sum_{i=1}^{n} CC_{i,pos} + \sum_{j=1}^{m} |CC_{j,neg}|}$, where $CC_{i,neg}$ is the climate change indicator value per functional unit of processes providing negative impact (avoided effects as for instance electricity recovery).

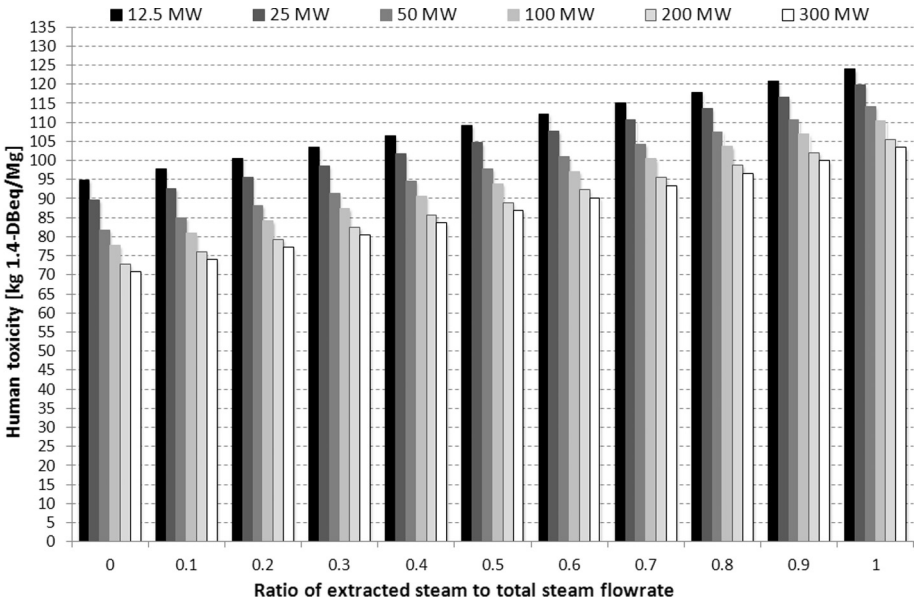

Fig. 8. Human toxicity indicator, for different plant sizes, vs. the fraction of steam extracted at 3 bar.

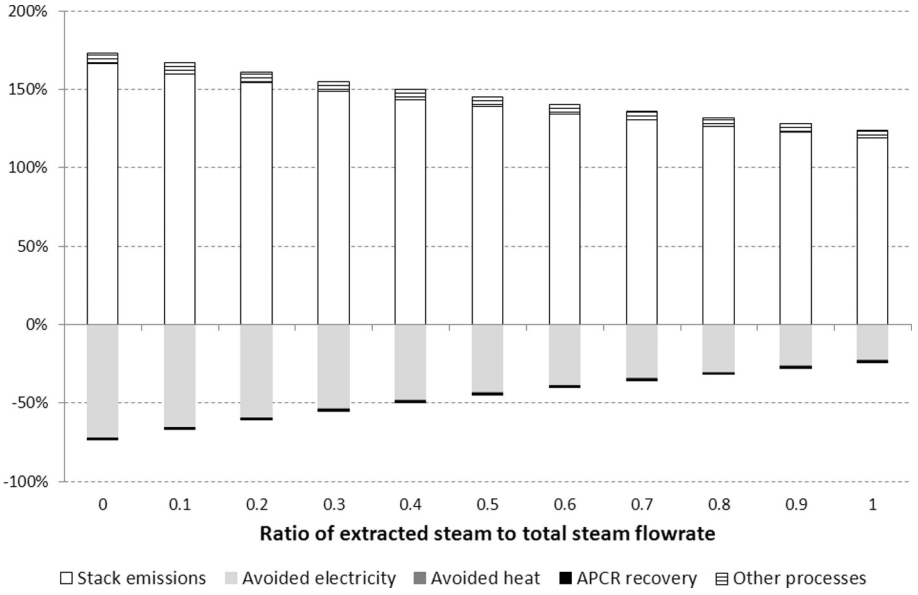

Fig. 9. Contributions to human toxicity indicator from processes included in the analyzed system vs. the fraction of steam extracted at 3 bar. Results are reported in the case of 50 MW plant size.

effects are included in the calculation. It is clear that reducing the transportation distance for the large plants has a beneficial effects: in the 300 MW case, the climate change indicator obtains a negative values when the distance is put to 100 km (in place of the original 200 km). Thus the transportation parameter plays a role, even if of minor importance, in the climate change value formation. In general the shorter the distance the lower the contribution. For instance, in the case of large plants (200–300 MW), if waste are imported from long distances as 1000 km (i.e. the case of transboundary transportation), the transport phase contribution to the positive effects is 22.5% (12.4% if also the absolute values of the avoided effects are included in the calculation). The positive impact of transport in this case significantly hinders the benefit of energy recovery.

Thus, detailed information about transportation distance is required to obtain reliable results for specific cases. Waste transport impact should be always considered carefully in waste management planning.

3.5. Improvements

As an improvement with respect to the base analyzed system, in which BA is directly landfilled, we considered the possibility of processing BA with the aim of recovering metals and inert materials, according to the assumptions already described in Section 2.2.3.

Fig. 11 shows the percent contribution of BA recovery to each impact indicator, compared with the base case of direct landfilling

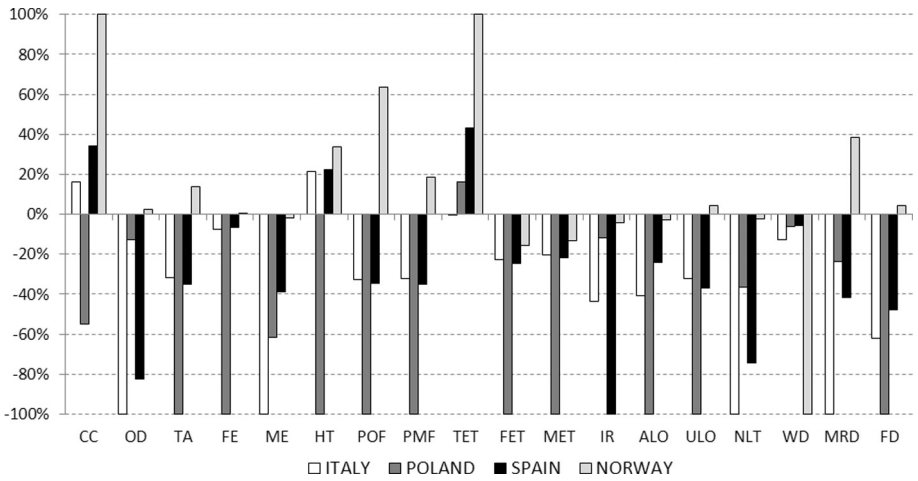

Fig. 10. Comparison of impact assessment indicator values for the four electricity mix cases of Italy, Poland, Spain and Norway, in the case of 50 MW WtE plant size and power production only mode.

Table 5
Average transportation distances assumed for the entering MSW.

Base case – size [MW]	*12.5*	*25*	*50*	*100*	*200*	*300*
Total [$kgCO_2$ eq./Mg]	147.69	119.48	73.04	51.54	20.45	6.67
Transport [$kgCO_2$ eq./Mg]	3.33	6.66	13.31	13.31	26.62	26.62
Contribution to positive effects	0.7%	1.4%	2.8%	2.8%	5.5%	5.5%
Contribution to total effects	0.4%	0.8%	1.5%	1.5%	2.8%	2.8%
Modified case 100 km – Size [MW]	*12.5*	*25*	*50*	*100*	*200*	*300*
Total [$kgCO_2$ eq./Mg]	157.68	126.14	73.04	51.54	7.14	−6.64
Transport [$kgCO_2$ eq./Mg]	13.31	13.31	13.31	13.31	13.31	13.31
Contribution to positive effects	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%
Contribution to total effects	1.7%	1.6%	1.5%	1.5%	1.4%	1.4%
Modified case 1000 km – Size [MW]	*12.5*	*25*	*50*	*100*	*200*	*300*
Total [$kgCO_2$ eq./Mg]	–	–	–	–	126.95	113.17
Transport [$kgCO_2$ eq./Mg]	–	–	–	–	133.12	133.12
Contribution to positive effects	–	–	–	–	22.5%	22.5%
Contribution to total effects	–	–	–	–	12.6%	12.4%

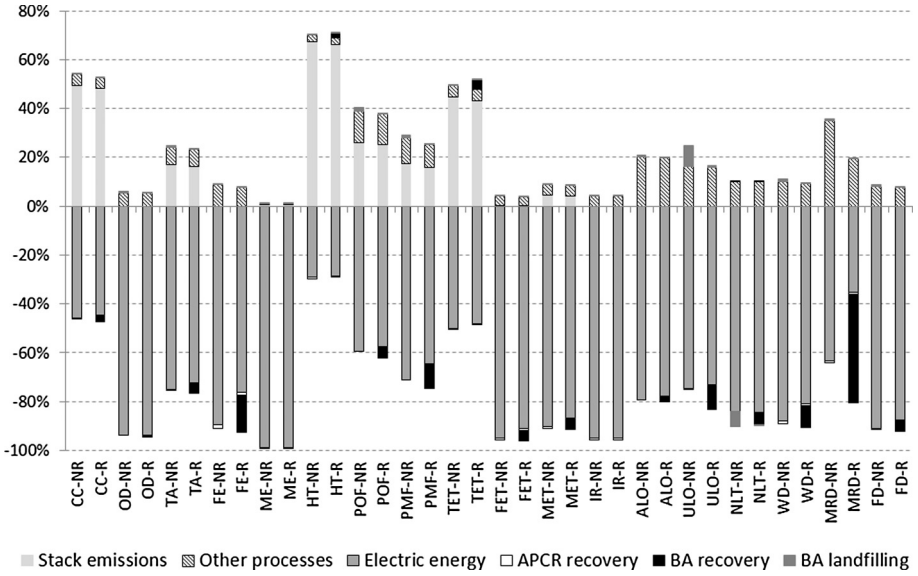
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
CC-NR CC-R OD-NR OD-R TA-NR TA-R FE-NR FE-R ME-NR ME-R HT-NR HT-R POF-NR POF-R PMF-NR PMF-R TET-NR TET-R FET-NR FET-R MET-NR MET-R IR-NR IR-R ALO-NR ALO-R ULO-NR ULO-R NLT-NR NLT-R WD-NR WD-R MRD-NR MRD-R FD-NR FD-R
Stack emissions Other processes Electric energy APCR recovery BA recovery BA landfilling

Fig. 11. Comparison of the contributions to the impact assessment indicator values for base case (no recovery (NR) of BA) and the improved case (recovery (R) of BA), in the case of 50 MW WtE plant size and power production only mode.

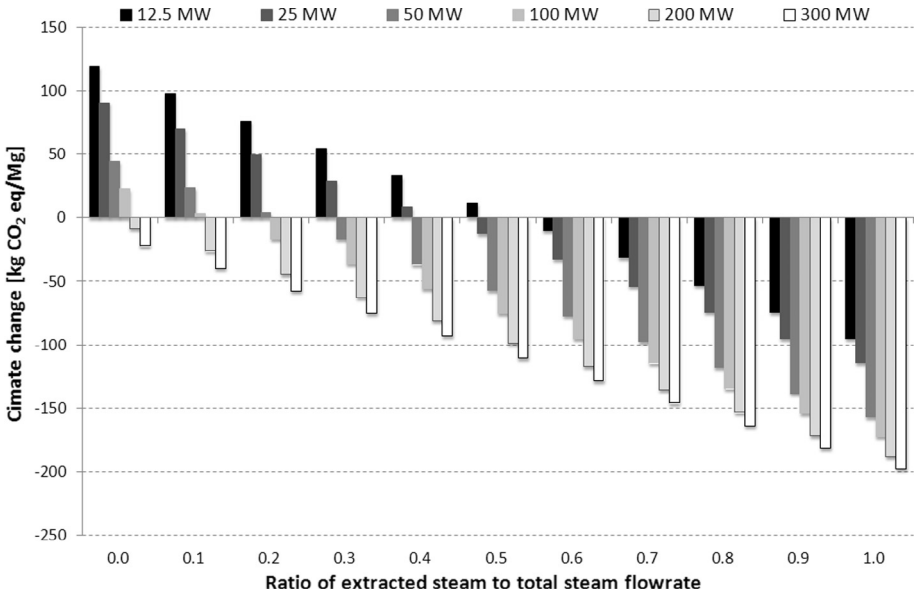

Fig. 12. Climate change indicator, for different plant sizes, vs. the fraction of steam extracted at 3 bar. Improved case: BA recovery.

of BA, in the case of only power production for the 50 MW size. The values of all the indicators improve, with the exception of human toxicity and terrestrial ecotoxicity. The percent contribution of BA recovery can be very significant in some cases, such as the freshwater eutrophication, photochemical oxidant formation, particulate matter formation, freshwater ecotoxicity, marine ecotoxicity and obviously metal resource depletion indicators. In the case of climate change, the indicator value falls from 73 to 44 kg of CO_2eq. per Mg of MSW. While the contribution to climate change due to BA landfilling in the reference scenario was equal to 19 kg of CO_2eq. per Mg of BA, it passes to −194 kg of CO_2eq. per Mg of BA in the BA recovery scenario. If the climate change indicator values are plotted again for the different plant sizes and for increasing cogeneration rate (Fig. 12), it is observed that the benefits achievable by the recovery of BA allow the WtE plants to operate as a carbon sink in a large number of cases with respect to the BA landfilling case (see Fig. 3). Even if the discussion about the cost aspects is out of the scope of this work, we like to add that, with reference to the Italian market, the landfilling cost for BA ranges presently from 50 to 70 Euro/Mg, while the recovery plants located in the North of Italy apply fees lower than 50 Euro/Mg.

4. Conclusions

Life Cycle Assessment was applied to evaluate the environmental impacts of an MSW WtE plant, considering different sizes and operation in different ways, from power production only to full cogeneration. The impact assessment results were calculated using the ReCiPe 2008 methods.

The negative values for the climate change indicator can be reached only by cogeneration of heat and power, with increasing ratios for decreasing size. The increasing cogeneration rate is beneficial with respect to the climate change indicator for all the plant sizes. Similarly, the fossil fuel depletion indicator benefits from increase of both the plant size and the cogeneration rate, but it is always negative, meaning that the residual MSW burning with energy recovery always provides a saving of fossil primary energy.

Other indicator values (ozone depletion, terrestrial acidification, photochemical oxidant formation, freshwater eutrophication, marine eutrophication, particulate matter formation, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, mineral depletion, water depletion, agricultural land occupation, urban land occupation and natural land transformation) are in general negative and are also beneficially affected by increasing the plant size, but they worsen when increasing the cogeneration rate. The remaining indicators – i.e. human toxicity and terrestrial ecotoxicity – always have positive values, which decrease for increasing plant size and increase as the cogeneration rate increases.

Thus the different indicators do not provide a homogeneous indication in order to reduce the different environmental effects. They cannot be improved simultaneously by applying the same strategy (i.e. increasing/reducing the size; only power production/cogeneration; increasing/decreasing the cogeneration rate). Priorities among the environmental indicators must be set by decision makers, taking into considerations local environmental conditions, economic and social factors. It is also important to emphasize that the plant size and the cogeneration level are often constrained by the local conditions. The plant size is generally decided on the basis of the population to be served, which in turn depends on the national and regional regulations defining the rules for the local planning of the integrated waste management system. The possibility of applying cogeneration depends on the effective presence of a customer (industrial plants or district heating) to whom the heat can be sold. The final decision is likely made on the basis of the cost issues, considering the revenues that can come from selling the electricity and/or the heat.

Additionally, the local context should be evaluated carefully with reference to the type of electricity which is substituted and in view of a future massive production of renewable electricity.

Finally, it was evaluated that the inclusion of bottom ash recovery – in place of landfilling – can significantly improve the values of several of the impact assessment indicators.

Acknowledgments

The students who contributed during their master thesis to the development of this work are fully acknowledged.

Appendix A

Size [MW]	Ratio of extracted steam to total steam flowrate										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Climate change											
12.5	1.48E+02	1.26E+02	1.05E+02	8.32E+01	6.17E+01	4.02E+01	1.88E+01	−2.75E+00	−2.42E+01	−4.58E+01	−6.60E+01
25	1.19E+02	9.89E+01	7.83E+01	5.76E+01	3.70E+01	1.64E+01	−4.08E+00	−2.49E+01	−4.55E+01	−6.60E+01	−8.53E+01
50	7.30E+01	5.28E+01	3.26E+01	1.23E+01	−7.98E+00	−2.82E+01	−4.84E+01	−6.87E+01	−8.89E+01	−1.09E+02	−1.28E+02
100	5.15E+01	3.19E+01	1.23E+01	−7.28E+00	−2.69E+01	−4.66E+01	−6.62E+01	−8.57E+01	−1.05E+02	−1.25E+02	−1.43E+02
200	2.05E+01	2.34E+00	−1.58E+01	−3.39E+01	−5.20E+01	−7.01E+01	−8.83E+01	−1.06E+02	−1.24E+02	−1.43E+02	−1.59E+02
300	6.67E+00	−1.10E+01	−2.87E+01	−4.64E+01	−6.41E+01	−8.18E+01	−9.95E+01	−1.17E+02	−1.35E+02	−1.53E+02	−1.69E+02
Ozone depletion											
12.5	−4.27E−05	−3.99E−05	−3.71E−05	−3.44E−05	−3.16E−05	−2.89E−05	−2.61E−05	−2.33E−05	−2.06E−05	−1.78E−05	−1.49E−05
25	−4.66E−05	−4.38E−05	−4.09E−05	−3.80E−05	−3.52E−05	−3.23E−05	−2.94E−05	−2.66E−05	−2.37E−05	−2.08E−05	−1.78E−05
50	−5.31E−05	−5.00E−05	−4.70E−05	−4.39E−05	−4.08E−05	−3.77E−05	−3.46E−05	−3.15E−05	−2.85E−05	−2.54E−05	−2.21E−05
100	−5.62E−05	−5.31E−05	−5.00E−05	−4.68E−05	−4.37E−05	−4.06E−05	−3.75E−05	−3.44E−05	−3.13E−05	−2.81E−05	−2.48E−05
200	−6.04E−05	−5.73E−05	−5.41E−05	−5.10E−05	−4.79E−05	−4.48E−05	−4.17E−05	−3.86E−05	−3.55E−05	−3.24E−05	−2.90E−05
300	−6.23E−05	−5.92E−05	−5.61E−05	−5.30E−05	−4.99E−05	−4.68E−05	−4.37E−05	−4.06E−05	−3.75E−05	−3.44E−05	−3.11E−05
Terrestrial acidification											
12.5	−7.60E−01	−7.04E−01	−6.48E−01	−5.92E−01	−5.36E−01	−4.80E−01	−4.24E−01	−3.69E−01	−3.12E−01	−2.57E−01	−1.96E−01
25	−8.66E−01	−8.08E−01	−7.49E−01	−6.90E−01	−6.31E−01	−5.72E−01	−5.13E−01	−4.54E−01	−3.96E−01	−3.37E−01	−2.73E−01
50	−1.04E+00	−9.73E−01	−9.09E−01	−8.45E−01	−7.81E−01	−7.16E−01	−6.52E−01	−5.88E−01	−5.24E−01	−4.59E−01	−3.90E−01
100	−1.12E+00	−1.06E+00	−9.93E−01	−9.28E−01	−8.63E−01	−7.97E−01	−7.32E−01	−6.67E−01	−6.01E−01	−5.36E−01	−4.65E−01
200	−1.22E+00	−1.15E+00	−1.09E+00	−1.02E+00	−9.57E−01	−8.91E−01	−8.25E−01	−7.59E−01	−6.93E−01	−6.27E−01	−5.55E−01
300	−1.27E+00	−1.21E+00	−1.14E+00	−1.08E+00	−1.01E+00	−9.44E−01	−8.78E−01	−8.13E−01	−7.47E−01	−6.81E−01	−6.09E−01
Freshwater eutrophication											
12.5	−4.61E−02	−4.30E−02	−3.99E−02	−3.68E−02	−3.37E−02	−3.06E−02	−2.75E−02	−2.44E−02	−2.13E−02	−1.82E−02	−1.49E−02
25	−5.09E−02	−4.77E−02	−4.44E−02	−4.12E−02	−3.80E−02	−3.48E−02	−3.16E−02	−2.84E−02	−2.51E−02	−2.19E−02	−1.85E−02
50	−5.88E−02	−5.53E−02	−5.19E−02	−4.84E−02	−4.50E−02	−4.15E−02	−3.80E−02	−3.46E−02	−3.11E−02	−2.77E−02	−2.40E−02
100	−6.23E−02	−5.88E−02	−5.53E−02	−5.18E−02	−4.83E−02	−4.48E−02	−4.13E−02	−3.78E−02	−3.43E−02	−3.08E−02	−2.71E−02
200	−6.82E−02	−6.47E−02	−6.12E−02	−5.77E−02	−5.42E−02	−5.07E−02	−4.72E−02	−4.37E−02	−4.02E−02	−3.67E−02	−3.30E−02
300	−7.04E−02	−6.69E−02	−6.34E−02	−5.99E−02	−5.64E−02	−5.30E−02	−4.95E−02	−4.60E−02	−4.25E−02	−3.90E−02	−3.53E−02
Marine eutrophication											
12.5	−2.02E+00	−1.89E+00	−1.76E+00	−1.63E+00	−1.50E+00	−1.37E+00	−1.24E+00	−1.11E+00	−9.78E−01	−8.48E−01	−7.10E−01
25	−2.22E+00	−2.09E+00	−1.95E+00	−1.82E+00	−1.68E+00	−1.55E+00	−1.41E+00	−1.28E+00	−1.14E+00	−1.01E+00	−8.67E−01
50	−2.57E+00	−2.42E+00	−2.28E+00	−2.13E+00	−1.99E+00	−1.84E+00	−1.70E+00	−1.55E+00	−1.41E+00	−1.26E+00	−1.11E+00
100	−2.71E+00	−2.56E+00	−2.41E+00	−2.27E+00	−2.12E+00	−1.98E+00	−1.83E+00	−1.68E+00	−1.54E+00	−1.39E+00	−1.23E+00
200	−2.99E+00	−2.84E+00	−2.70E+00	−2.55E+00	−2.41E+00	−2.26E+00	−2.11E+00	−1.97E+00	−1.82E+00	−1.68E+00	−1.52E+00
300	−3.08E+00	−2.93E+00	−2.79E+00	−2.64E+00	−2.50E+00	−2.35E+00	−2.21E+00	−2.06E+00	−1.92E+00	−1.77E+00	−1.62E+00
Human toxicity											
12.5	9.48E+01	9.77E+01	1.01E+02	1.03E+02	1.06E+02	1.09E+02	1.12E+02	1.15E+02	1.18E+02	1.21E+02	1.24E+02
25	8.96E+01	9.26E+01	9.56E+01	9.86E+01	1.02E+02	1.05E+02	1.08E+02	1.11E+02	1.14E+02	1.17E+02	1.20E+02
50	8.18E+01	8.50E+01	8.82E+01	9.14E+01	9.46E+01	9.79E+01	1.01E+02	1.04E+02	1.08E+02	1.11E+02	1.14E+02
100	7.76E+01	8.09E+01	8.41E+01	8.74E+01	9.06E+01	9.39E+01	9.71E+01	1.00E+02	1.04E+02	1.07E+02	1.10E+02
200	7.27E+01	7.60E+01	7.92E+01	8.25E+01	8.57E+01	8.90E+01	9.22E+01	9.55E+01	9.87E+01	1.02E+02	1.05E+02
300	7.08E+01	7.40E+01	7.72E+01	8.05E+01	8.37E+01	8.69E+01	9.02E+01	9.34E+01	9.66E+01	9.99E+01	1.03E+02
Photochemical oxidant formation											
12.5	−1.89E−01	−1.66E−01	−1.42E−01	−1.19E−01	−9.59E−02	−7.26E−02	−4.94E−02	−2.62E−02	−2.95E−03	2.02E−02	4.63E−02
25	−2.32E−01	−2.07E−01	−1.82E−01	−1.57E−01	−1.32E−01	−1.07E−01	−8.23E−02	−5.74E−02	−3.24E−02	−7.40E−03	2.06E−02
50	−2.93E−01	−2.65E−01	−2.37E−01	−2.09E−01	−1.82E−01	−1.54E−01	−1.26E−01	−9.79E−02	−7.00E−02	−4.22E−02	−1.09E−02
100	−3.46E−01	−3.17E−01	−2.89E−01	−2.60E−01	−2.31E−01	−2.03E−01	−1.74E−01	−1.45E−01	−1.17E−01	−8.82E−02	−5.62E−02
200	−3.19E−01	−2.90E−01	−2.60E−01	−2.31E−01	−2.02E−01	−1.72E−01	−1.43E−01	−1.13E−01	−8.40E−02	−5.46E−02	−2.18E−02
300	−3.51E−01	−3.21E−01	−2.92E−01	−2.63E−01	−2.33E−01	−2.03E−01	−1.74E−01	−1.45E−01	−1.15E−01	−8.55E−02	−5.26E−02
Particulate matter formation											
12.5	−2.11E−01	−1.93E−01	−1.75E−01	−1.56E−01	−1.38E−01	−1.19E−01	−1.01E−01	−8.27E−02	−6.42E−02	−4.59E−02	−2.59E−02
25	−2.43E−01	−2.23E−01	−2.04E−01	−1.85E−01	−1.65E−01	−1.46E−01	−1.27E−01	−1.08E−01	−8.82E−02	−6.89E−02	−4.80E−02
50	−2.92E−01	−2.71E−01	−2.50E−01	−2.29E−01	−2.08E−01	−1.87E−01	−1.66E−01	−1.45E−01	−1.24E−01	−1.03E−01	−8.00E−02
100	−3.19E−01	−2.98E−01	−2.77E−01	−2.55E−01	−2.34E−01	−2.13E−01	−1.91E−01	−1.70E−01	−1.49E−01	−1.27E−01	−1.04E−01
200	−3.40E−01	−3.19E−01	−2.97E−01	−2.76E−01	−2.54E−01	−2.33E−01	−2.11E−01	−1.90E−01	−1.68E−01	−1.47E−01	−1.23E−01
300	−3.57E−01	−3.36E−01	−3.14E−01	−2.93E−01	−2.71E−01	−2.50E−01	−2.28E−01	−2.07E−01	−1.85E−01	−1.64E−01	−1.40E−01
Terrestrial ecotoxicity											
12.5	4.88E−03	6.12E−03	7.36E−03	8.61E−03	9.85E−03	1.11E−02	1.23E−02	1.36E−02	1.48E−02	1.61E−02	1.74E−02
25	2.97E−03	4.26E−03	5.55E−03	6.84E−03	8.13E−03	9.42E−03	1.07E−02	1.20E−02	1.33E−02	1.46E−02	1.60E−02
50	−3.94E−05	1.35E−03	2.74E−03	4.13E−03	5.52E−03	6.90E−03	8.30E−03	9.68E−03	1.11E−02	1.25E−02	1.39E−02
100	−1.60E−03	−1.97E−04	1.21E−03	2.61E−03	4.01E−03	5.42E−03	6.82E−03	8.23E−03	9.63E−03	1.10E−02	1.25E−02

Appendix A (*continued*)

Size [MW]	Ratio of extracted steam to total steam flowrate										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
200	−3.30E−03	−1.89E−03	−4.91E−04	9.12E−04	2.32E−03	3.72E−03	5.12E−03	6.52E−03	7.93E−03	9.33E−03	1.08E−02
300	−4.18E−03	−2.78E−03	−1.38E−03	1.15E−05	1.41E−03	2.81E−03	4.21E−03	5.61E−03	7.01E−03	8.41E−03	9.90E−03
Freshwater ecotoxicity											
12.5	−2.63E+00	−2.46E+00	−2.28E+00	−2.11E+00	−1.93E+00	−1.76E+00	−1.59E+00	−1.41E+00	−1.24E+00	−1.07E+00	−8.81E−01
25	−2.89E+00	−2.71E+00	−2.53E+00	−2.35E+00	−2.17E+00	−1.99E+00	−1.81E+00	−1.63E+00	−1.45E+00	−1.27E+00	−1.08E+00
50	−3.33E+00	−3.14E+00	−2.95E+00	−2.75E+00	−2.56E+00	−2.37E+00	−2.17E+00	−1.98E+00	−1.79E+00	−1.59E+00	−1.39E+00
100	−3.52E+00	−3.32E+00	−3.13E+00	−2.93E+00	−2.74E+00	−2.54E+00	−2.35E+00	−2.15E+00	−1.96E+00	−1.76E+00	−1.55E+00
200	−3.86E+00	−3.67E+00	−3.47E+00	−3.28E+00	−3.08E+00	−2.89E+00	−2.69E+00	−2.50E+00	−2.31E+00	−2.11E+00	−1.90E+00
300	−3.98E+00	−3.79E+00	−3.60E+00	−3.40E+00	−3.21E+00	−3.01E+00	−2.82E+00	−2.62E+00	−2.43E+00	−2.24E+00	−2.03E+00
Marine ecotoxicity											
12.5	−2.15E+00	−2.00E+00	−1.85E+00	−1.70E+00	−1.55E+00	−1.39E+00	−1.24E+00	−1.09E+00	−9.36E−01	−7.84E−01	−6.22E−01
25	−2.38E+00	−2.23E+00	−2.07E+00	−1.91E+00	−1.75E+00	−1.60E+00	−1.44E+00	−1.28E+00	−1.12E+00	−9.65E−01	−7.97E−01
50	−2.77E+00	−2.60E+00	−2.43E+00	−2.26E+00	−2.09E+00	−1.92E+00	−1.75E+00	−1.58E+00	−1.41E+00	−1.24E+00	−1.06E+00
100	−2.93E+00	−2.76E+00	−2.59E+00	−2.42E+00	−2.25E+00	−2.08E+00	−1.91E+00	−1.73E+00	−1.56E+00	−1.39E+00	−1.21E+00
200	−3.22E+00	−3.05E+00	−2.88E+00	−2.71E+00	−2.54E+00	−2.37E+00	−2.20E+00	−2.03E+00	−1.86E+00	−1.69E+00	−1.51E+00
300	−3.33E+00	−3.16E+00	−2.99E+00	−2.82E+00	−2.65E+00	−2.48E+00	−2.31E+00	−2.14E+00	−1.97E+00	−1.80E+00	−1.62E+00
Ionising radiation											
12.5	−5.29E+01	−4.95E+01	−4.62E+01	−4.28E+01	−3.94E+01	−3.61E+01	−3.27E+01	−2.93E+01	−2.59E+01	−2.26E+01	−1.90E+01
25	−5.81E+01	−5.46E+01	−5.11E+01	−4.76E+01	−4.41E+01	−4.06E+01	−3.71E+01	−3.36E+01	−3.01E+01	−2.66E+01	−2.29E+01
50	−6.67E+01	−6.29E+01	−5.92E+01	−5.54E+01	−5.17E+01	−4.79E+01	−4.41E+01	−4.04E+01	−3.66E+01	−3.29E+01	−2.89E+01
100	−7.04E+01	−6.66E+01	−6.28E+01	−5.90E+01	−5.52E+01	−5.14E+01	−4.77E+01	−4.39E+01	−4.01E+01	−3.63E+01	−3.22E+01
200	−7.69E+01	−7.31E+01	−6.94E+01	−6.56E+01	−6.18E+01	−5.80E+01	−5.42E+01	−5.04E+01	−4.66E+01	−4.28E+01	−3.88E+01
300	−7.93E+01	−7.55E+01	−7.18E+01	−6.80E+01	−6.42E+01	−6.04E+01	−5.66E+01	−5.29E+01	−4.91E+01	−4.53E+01	−4.13E+01
Water depletion											
12.5	−1.90E+00	−1.75E+00	−1.60E+00	−1.45E+00	−1.30E+00	−1.14E+00	−9.94E−01	−8.44E−01	−6.93E−01	−5.42E−01	−3.83E−01
25	−2.10E+00	−1.95E+00	−1.79E+00	−1.64E+00	−1.48E+00	−1.32E+00	−1.17E+00	−1.01E+00	−8.58E−01	−7.02E−01	−5.38E−01
50	−2.44E+00	−2.28E+00	−2.11E+00	−1.94E+00	−1.78E+00	−1.61E+00	−1.44E+00	−1.28E+00	−1.11E+00	−9.43E−01	−7.67E−01
100	−2.59E+00	−2.42E+00	−2.25E+00	−2.09E+00	−1.92E+00	−1.75E+00	−1.58E+00	−1.41E+00	−1.25E+00	−1.08E+00	−9.01E−01
200	−2.84E+00	−2.68E+00	−2.51E+00	−2.34E+00	−2.17E+00	−2.01E+00	−1.84E+00	−1.67E+00	−1.51E+00	−1.34E+00	−1.16E+00
300	−2.94E+00	−2.77E+00	−2.61E+00	−2.44E+00	−2.27E+00	−2.11E+00	−1.94E+00	−1.77E+00	−1.61E+00	−1.44E+00	−1.26E+00
Mineral resource depletion											
12.5	−2.93E+00	−2.81E+00	−2.69E+00	−2.57E+00	−2.45E+00	−2.32E+00	−2.20E+00	−2.08E+00	−1.96E+00	−1.84E+00	−1.69E+00
25	−3.55E+00	−3.41E+00	−3.27E+00	−3.13E+00	−2.99E+00	−2.85E+00	−2.71E+00	−2.57E+00	−2.42E+00	−2.28E+00	−2.11E+00
50	−4.55E+00	−4.38E+00	−4.21E+00	−4.04E+00	−3.87E+00	−3.70E+00	−3.53E+00	−3.36E+00	−3.19E+00	−3.02E+00	−2.82E+00
100	−5.09E+00	−4.91E+00	−4.73E+00	−4.55E+00	−4.37E+00	−4.20E+00	−4.02E+00	−3.84E+00	−3.66E+00	−3.48E+00	−3.26E+00
200	−5.51E+00	−5.32E+00	−5.13E+00	−4.93E+00	−4.74E+00	−4.55E+00	−4.36E+00	−4.17E+00	−3.97E+00	−3.78E+00	−3.55E+00
300	−5.86E+00	−5.66E+00	−5.47E+00	−5.27E+00	−5.08E+00	−4.88E+00	−4.69E+00	−4.50E+00	−4.30E+00	−4.11E+00	−3.87E+00
Fossil fuel depletion											
12.5	−8.86E+01	−9.66E+01	−1.05E+02	−1.13E+02	−1.21E+02	−1.29E+02	−1.37E+02	−1.45E+02	−1.53E+02	−1.61E+02	−1.68E+02
25	−9.71E+01	−1.05E+02	−1.13E+02	−1.20E+02	−1.28E+02	−1.36E+02	−1.44E+02	−1.51E+02	−1.59E+02	−1.67E+02	−1.74E+02
50	−1.11E+02	−1.19E+02	−1.26E+02	−1.34E+02	−1.42E+02	−1.50E+02	−1.57E+02	−1.65E+02	−1.73E+02	−1.80E+02	−1.87E+02
100	−1.18E+02	−1.25E+02	−1.33E+02	−1.40E+02	−1.48E+02	−1.55E+02	−1.63E+02	−1.70E+02	−1.78E+02	−1.85E+02	−1.92E+02
200	−1.27E+02	−1.34E+02	−1.41E+02	−1.48E+02	−1.55E+02	−1.61E+02	−1.68E+02	−1.75E+02	−1.82E+02	−1.89E+02	−1.96E+02
300	−1.31E+02	−1.38E+02	−1.45E+02	−1.51E+02	−1.58E+02	−1.65E+02	−1.72E+02	−1.79E+02	−1.85E+02	−1.92E+02	−1.99E+02
Agricultural land occupation											
12.5	−8.48E+00	−7.67E+00	−6.86E+00	−6.06E+00	−5.25E+00	−4.44E+00	−3.63E+00	−2.83E+00	−2.02E+00	−1.21E+00	−3.53E−01
25	−9.73E+00	−8.90E+00	−8.06E+00	−7.22E+00	−6.39E+00	−5.55E+00	−4.71E+00	−3.88E+00	−3.04E+00	−2.20E+00	−1.32E+00
50	−1.18E+01	−1.09E+01	−1.00E+01	−9.14E+00	−8.24E+00	−7.35E+00	−6.45E+00	−5.55E+00	−4.65E+00	−3.75E+00	−2.80E+00
100	−1.27E+01	−1.18E+01	−1.09E+01	−9.98E+00	−9.07E+00	−8.16E+00	−7.26E+00	−6.35E+00	−5.44E+00	−4.53E+00	−3.57E+00
200	−1.44E+01	−1.35E+01	−1.26E+01	−1.17E+01	−1.08E+01	−9.90E+00	−9.00E+00	−8.09E+00	−7.19E+00	−6.28E+00	−5.32E+00
300	−1.50E+01	−1.41E+01	−1.32E+01	−1.23E+01	−1.14E+01	−1.05E+01	−9.57E+00	−8.67E+00	−7.77E+00	−6.86E+00	−5.90E+00
Urban land occupation											
12.5	−7.33E−01	−6.64E−01	−5.96E−01	−5.27E−01	−4.59E−01	−3.90E−01	−3.21E−01	−2.53E−01	−1.84E−01	−1.16E−01	−4.29E−02
25	−8.04E−01	−7.33E−01	−6.62E−01	−5.91E−01	−5.20E−01	−4.49E−01	−3.78E−01	−3.07E−01	−2.36E−01	−1.65E−01	−8.93E−02
50	−9.12E−01	−8.36E−01	−7.59E−01	−6.83E−01	−6.07E−01	−5.31E−01	−4.54E−01	−3.78E−01	−3.02E−01	−2.26E−01	−1.45E−01
100	−9.85E−01	−9.08E−01	−8.31E−01	−7.54E−01	−6.77E−01	−6.00E−01	−5.23E−01	−4.46E−01	−3.69E−01	−2.92E−01	−2.10E−01
200	−9.91E−01	−9.14E−01	−8.37E−01	−7.61E−01	−6.84E−01	−6.07E−01	−5.30E−01	−4.53E−01	−3.76E−01	−3.00E−01	−2.18E−01
300	−1.04E+00	−9.61E−01	−8.85E−01	−8.08E−01	−7.32E−01	−6.55E−01	−5.79E−01	−5.02E−01	−4.25E−01	−3.49E−01	−2.67E−01
Natural land transformation											
12.5	−5.15E−02	−4.83E−02	−4.50E−02	−4.18E−02	−3.85E−02	−3.53E−02	−3.20E−02	−2.88E−02	−2.56E−02	−2.23E−02	−1.89E−02
25	−5.54E−02	−5.20E−02	−4.87E−02	−4.53E−02	−4.19E−02	−3.86E−02	−3.52E−02	−3.19E−02	−2.85E−02	−2.51E−02	−2.16E−02

(*continued on next page*)

Appendix A (*continued*)

Size [MW]	Ratio of extracted steam to total steam flowrate										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
50	−6.15E−02	−5.79E−02	−5.43E−02	−5.07E−02	−4.71E−02	−4.35E−02	−3.99E−02	−3.63E−02	−3.27E−02	−2.91E−02	−2.52E−02
100	−6.50E−02	−6.13E−02	−5.77E−02	−5.41E−02	−5.04E−02	−4.68E−02	−4.31E−02	−3.95E−02	−3.58E−02	−3.22E−02	−2.83E−02
200	−6.73E−02	−6.37E−02	−6.01E−02	−5.64E−02	−5.28E−02	−4.91E−02	−4.55E−02	−4.19E−02	−3.82E−02	−3.46E−02	−3.07E−02
300	−6.95E−02	−6.59E−02	−6.23E−02	−5.87E−02	−5.51E−02	−5.14E−02	−4.78E−02	−4.42E−02	−4.06E−02	−3.69E−02	−3.31E−02

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